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6. AUTHOR(S) David C. Fritts					
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13. ABSTRACT (Maximum 200 Words)  This grant supported numerical, theoretical, and observational studies of gravity wave and shear instability processes in the atmosphere and their impact on airglow layers near the mesopause. Among our results, two stand out in their importance. The first was numerical confirmation of the instability processes initiating the transition to turbulence in Kelvin-Helmholtz instability in an unstable shear flow. The second, and even more significant, was the identification of the vortex dynamics accounting for the transition to, and the cascade within, fully developed turbulence. We expect that these dynamics will play a critical role in virtually all turbulent flows and will thus be key to understanding turbulence transitions and effects in many geophysical and fluid applications. Also examined were the instability processes accompanying lower-frequency gravity waves, where similar transitions were found to occur and were found, in particular, to provide an explanation for apparent instability signatures in airglow data. Finally, we considered the dynamics and instabilities accompanying vortex pairs in two and three dimensions analytically and numerically. Environmental shear and stratification were found to have large influences on the occurrence and character of instabilities, suggesting that turbulence transitions and effects cannot be anticipated without knowledge of these fields.					
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## FINAL TASK REPORT

**Instructions:** Provide all information identified below for the duration of this project. List "Research Objectives" in bullet format. Provide "Summary of Research" in narrative format.

Research Title: Gravity Wave Modeling and Airglow Applications

Principal Investigator: David C. Fritts

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AFOSR Program Manager: Major Paul Bellaire JR.

### Research Objectives:

- examine the dynamics and instability processes accompanying gravity wave breaking
- examine the transition to turbulence in stratified and sheared flows
- examine airglow responses to wave and instability processes near the mesopause

### Summary of Research Results:

Our efforts under this AFOSR research support have led to a number of new, and we believe significant, scientific results in four distinct areas. Our compressible simulations of Kelvin-Helmholtz (KH) instability (Fritts et al., 1996; Palmer et al., 1996) were among the first to identify the character and dynamics of the secondary instability leading to turbulence within a KH billow at sufficiently high Reynolds numbers to trigger the transition to turbulence. These studies both 1) defined the scales, energy sources, and morphology of the streamwise-aligned instability accounting for KH breakdown and 2) delineated the importance of this three-dimensional (3D) structure in departures from a corresponding (and nonphysical) two-dimensional (2D) flow evolution. We also examined in detail the dynamics of the entrainment region into the billow and discovered that baroclinic tendencies operating there conditioned the flow to have strong shear (or inertial) sources of instability kinetic energy in addition to the convective sources anticipated earlier theoretical efforts. These studies appear to be regarded as the definitive KH studies to date, despite our newer, and higher-resolution, studies which have yet to appear.

A second area in which we have broken new ground is in the application of numerical simulations of wave breaking and instability processes to observations of atmospheric airglow. Following our earlier application of a compressible simulation of high-frequency gravity wave breaking to the instability structures observed in noctilucent clouds, we performed simulations of low-frequency wave instability and the instability implications for superposed low- and higher-frequency wave motions. These studies defined the character of the instability of such lower-frequency motions and enabled an explanation of instability structures observed in airglow during the CORN campaign using radar, lidar, and airglow instrumentation in central Illinois (Hecht et al., 1997; Fritts et al., 1997).

Our most extensive efforts during the course of this research have focussed on the instability and vortex dynamics accompanying wave breaking. These efforts involved a combination of theoretical and analysis activities aimed at dissecting the 3D numerical data sets arising from our highest-resolution simulations with the compressible code. Our analyses revealed that the initial instabilities due to wave breaking are streamwise-aligned, counter-rotating rolls, closely associated with the dominant instability of KH billows discussed above. Because of the proximity of these rolls to adjacent strong spanwise vortex sheets, the rolls induce spanwise divergence and stretching of these sheets and a secondary dynamical instability of the sheets. This leads to a nest of orthogonally-aligned and closely-spaced vortices (Andreassen et al., 1998). These vortices thereafter undergo a series of interactions best characterized as the excitation and propagation of Kelvin vortex waves, or twist waves, which appear to drive the cascade toward smaller scales and increased isotropy (Fritts et al., 1998; Arendt et al., 1997, 1998). We speculated that these interactions should be common to, and may account for the turbulence cascade within, many geophysical flows. Indeed, our more recent KH simulations using an incompressible code at much higher resolution exhibits the same classes of interactions and provides evidence for this conjecture. If this proves to be true in more general flows, then this research effort will have contributed to what we hope will be a quantitative understanding of the dynamics underlying the turbulence cascade, a longstanding goal in fluid dynamics.

A separate effort used both numerical and analytic techniques to examine the evolution of a vortex pair in two and three dimensions in a flow having shear and stratification. The numerical studies (Garten et al., 1998) defined the dynamics of the vorticity field, including influences of baroclinicity and shear, on vortex propagation and instability. An analytic study by Arendt and Fritts (1998) addressed the influences on the 3D Crow instability of an external shear and made predictions about growth rates subsequently verified in additional 3D simulations not yet reported (Garten, private communication, 1998).

## Appendix A: In-house Activities

**Instructions:** Provide all information identified below for the duration of this project. "Personnel" should include each scientist or engineer who contributed to the research during the year. Publication of articles derived from the research should be listed chronologically in bibliography format. Attach reprints. List only invention disclosures derived from this specific research effort. Honors may include recognition both inside and outside the academic and Air Force science & technology (S&T) communities. Extended scientific visits may include collaboration with other research programs, both foreign and US.

### Personnel:

	<u>Name</u>	<u>Degree</u>	<u>Discipline</u>	<u>Involvement</u>
In House Employees	David C. Fritts	Ph.D.	Physicist	1mo/yr
	Jim Garten	Ph.D.student	Physicist	1/2 time
	Teresa Palmer	Ph.D.student	Physicist	1/2 time
	Mike Gourlay	Ph.D.student	Physicist	1/2 time
On-site Contractors				

### Visitors

### Publications:

- Fritts, D. C., Palmer, T. L., O. Andreassen, and I. Lie, 1996: Evolution and break-down of Kelvin-Helmholtz billows in stratified compressible flows, I: Comparison of two- and three-dimensional flows, J. Atmos. Sci., 53, 3173-3191.
- Palmer, T. L., D. C. Fritts, and O. Andreassen, 1996: Evolution and breakdown of Kelvin-Helmholtz billows in stratified compressible flows, II: Instability structure, evolution, and energetics, J. Atmos. Sci., 53, 3192-3212.
- Hecht, J. H., R. L. Walterscheid, D. C. Fritts, J. R. Isler, D. C. Senft, C. S. Gardner, and S. J. Franke, 1997: Wave breaking signatures in OH airglow and sodium densities and temperatures, Part I: Airglow imaging, Na lidar, and MF radar observations, J. Geophys. Res., 102, 6655-6668.
- Fritts, D. C., J. R. Isler, J. H. Hecht, and R. L. Walterscheid, 1997: Wave breaking signatures in OH airglow and sodium densities and temperatures, Part II: Airglow imaging, Na lidar, and MF radar observations, Part II: Simulation of wave and instability structures, J. Geophys. Res. 102, 6669-6684.
- Arendt, S., D. C. Fritts, and O. Andreassen, 1997: The initial value problem for Kelvin vortex waves, J. Fluid Mech., 344, 181-212.

- Arendt, S., and D. C. Fritts, 1998: The instability of a vortex tube in a weak external shear and strain, *Phys. Fluids*, 10, 530-532.
- Garten, J. F., D. C. Fritts, S. Arendt, and O. Andreassen, 1998: Dynamics of counter-rotating vortex pairs in stratified and sheared environments, *J. Fluid Mech.*, 361, 189-236.
- Andreassen, O., P.O. Hvidsten, D. C. Fritts, and S. Arendt, 1998: Vorticity dynamics in a breaking gravity wave, 1. Initial instability evolution, *J. Fluid Mech.*, 367, 27-46.
- Fritts, D. C., S. Arendt, and O. Andreassen, 1998: Vorticity dynamics in a breaking gravity wave, 2. Vortex interactions and transition to turbulence, *J. Fluid Mech.*, 367, 47-65.
- Arendt, S., D. C. Fritts, and O. Andreassen, 1998: Kelvin twist waves in the transition to turbulence, *Europ. Phys. Soc.*, in press.
- Technical Presentations:
- Garten, J. F., D. C. Fritts, and O. Andreassen, Simulations of a vortex pair in sheared and stratified environments, 10th AMS Conf. on Atmos. and Oceanic Waves and Stability, Big Sky, June 1995.
- Fritts, D. C., S. Arendt, and O. Andreassen, Vorticity dynamics in a breaking gravity wave, 10th AMS Conf. on Atmos. and Oceanic Waves and Stability, Big Sky, June 1995.
- Palmer, T. L., D. C. Fritts, and O. Andreassen, Three dimensional simulations of Kelvin-Helmholtz billows and secondary instabilities, 10th AMS Conf. on Atmos. and Oceanic Waves and Stability, Big Sky, June 1995.
- Fritts, D. C., Modeling of wave and instability processes in the middle atmosphere, CEDAR Prize Lecture, CEDAR Summer Symposium, Boulder, June 1995.
- Palmer, T. L., D. C. Fritts, and O. Andreassen, Two and three-dimensional simulations of Kelvin-Helmholtz billows and secondary instabilities, Int'l. Union of Geodesy and Geophysics General Assembly, Boulder, July 1995.
- Arendt, S., D. C. Fritts, and O. Andreassen, Dynamics of Kelvin waves on vortex tubes, 21st EGS Symposium on Vortex Dynamics, The Hague, May 1996.
- Arendt, S., D. C. Fritts, and O. Andreassen, Vortex tube evolution in a breaking gravity wave, 21st EGS Symposium on Vortex Dynamics, The Hague, May 1996.

Gourlay, M. J., D. C. Fritts, S. Arendt, and O. Andreassen, Instability and evolution of finite span vortex sheets, 21st EGS Symposium on Vortex Dynamics, The Hague, May 1996.

Garten, J. F., D. C. Fritts, S. Arendt, and O. Andreassen, Counter-rotating vortex tubes in a stably stratified fluid, 21st EGS Symposium on Vortex Dynamics, The Hague, May 1996.

Andreassen, O., S. Arendt, and D. C. Fritts, Formation of vortices and potential vorticity in the field of a breaking wave, 21st EGS Symposium on Vortex Dynamics, The Hague, May 1996.

Palmer, T. L., D. C. Fritts, and O. Andreassen, Secondary instability, breakdown, and restratification of Kelvin-Helmholtz billows at high Reynolds numbers, 21st EGS Symposium on Vortex Dynamics, The Hague, May 1996.

Garten, J. F., D. C. Fritts, and S. Arendt, Dynamics of counter-rotating vortices in stratification and shear, annual APS meeting, November 1996.

Arendt, S., D. C. Fritts, and O. Andreassen, Kelvin twist waves due to a breaking gravity wave, annual APS meeting, November 1996.

Arendt, S., D. C. Fritts, and O. Andreassen, Kelvin twist waves in the transition to turbulence, Euromech Symposium, Marseilles, June 1997.

Fritts, D. C., Gravity wave breaking: Instability dynamics and transition to turbulence, Int'l. Symp. on the Dynamics of the Mesopause Region, Kyoto, March 1998.

Invention Disclosures and Patents Granted: None

Invited Lectures, Presentations, Talks, etc.:

Invited Speaker, Int'l Workshop on Atmospheric Waves, Adelaide, September 1997.

Invited Speaker, Int'l. Sym. On the Dynamics of the Mesopause Region, Kyoto, March 1998.

**Professional Activities (editorships, conference and society committees, etc.):** CADRE (Coupling And Dynamics of Regions Equatorial measurement campaign coordinator and Guest Editor of JGR Special Issue (Nov. 1997), 1993 - 1997.

**Session Convenor and Chairman, Int'l. Union of Geodesy and Geophysics General Assembly, Boulder, July 1995.**

**Convenor and Session Chairman, IUGG Symposium, Uppsala August 1997.**

**Convenor and Session Chairman, Int'l. Sym. On the Dynamics of the Mesopause Region, Kyoto, March 1998.**

**President, International Commission on the Middle Atmosphere (ICMA), 1992 - 2002.**

**Honors Received (include lifetime honors such as Fellow, honorary doctorates, etc., stating year elected):**

**CEDAR Prize Lecturer, Summer CEDAR Symposium, June 1995.**

**Extended Scientific Visits From and To Other Laboratories:**

**Visiting Professor with the Radio Atmospheric Science Center, Kyoto University, Kyoto, Japan, September - December 1996.**

#### **Appendix B: Off-Site Contract and Grant Activities**

**Instructions:** Provide all information identified below for the last FY only. Publication of articles derived from the research should be listed chronologically in bibliography format. Attach reprints. List only invention disclosures derived from this specific research effort.

**Publications:** N/A

## Appendix C: Technology Transitions/Transfers Detailed Listing

### Tech transfers:

In association with this grant and using funding in place through colleagues at the Norwegian Defence Research Establishment, we have contributed to the development of a high-level graphics package for visualization of three-dimensional data sets in order to assist with our understanding of the complex flows accompanying transitions to turbulence. This package also appears to be potentially beneficial to other communities, particularly medical imaging and oil and gas exploration. Hence, we are in the process of making it widely available via distribution on the Web and installation at the DoD Major Shared Resource Centers. It will also be available to potential commercial customers, should such interest arise.

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